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Note on collective excitation of odd nuclei of supposed "spherical" core

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ABSTRACT

Aiming at a better understanding of some special excited states in the platinum isotopes, a search has been carried out for levels of possible collective character in odd nuclei. Some evidence has been found for this type of excitation in a few odd neutron nuclei.

Introduction

It is well known about even-even nuclei that the lowest excited states are generally the result of collective motion. The least well understood of these collective excitation phenomena are those occuring in nuclei in the approximate mass regions $75 < A < 140$ and $190 < A < 220$. Here, the two lowest excited states are usually of $2+$ character, and the energy of the second excited state is roughly twice that of the first one. The tendency of the first rotational state $(2+)$ of a deformed nucleus is an increase in excitation energy as a closed shell is approached, so that the energy of this state behaves smoothly in going into the "spherical" region. The trend of the higher $2+$ state is not as easily followed since the second $2+$ state in deformed nuclei has a high energy and the increase is rather abrupt so that a connection is not clearly suggested by the experimental data. The problem of the excitation of "spherical" nuclei may be treated theoretically in different ways in terms of the Bohr-Mottelsen theory. In a semi-quantitative treatment by Scharff-Goldhaber and Weneser [1] the nuclear surface was assumed to perform oscillations of the quadrupole type around a spherical equilibrium. This produced the desired $2+$ levels as a one phonon and a two phonon state, the latter being degenerate with the additional characters $0+$ and $4+$. The amount of experimental support for this theory may be judged from a recent survey of data [2]. The situation is that a $4+$ level has occationally been observed close to the usual $2+$ state, whereas a $0+$ level of the expected energy has rarely been observed, and only in one or two cases is it possible to speak of a full triplet state.

A second approach considers the possibility of a nuclear shape without axial summetry. Recent calculations by Davydov and Filipov [3] were performed on the assumption that the deformation is permanent and that the excitation is produced by rotation of the whole structure. While this modification does not change the conventional rotational spectrum of deformed nuclei it does produce a second rotational $2+$ state, which actually receives twice the energy of the first one, or more, depending on the deformation parameter. No 0+ state is produced in this mode of excitation, but a 4+ state may come rather close to the second 2+ state. The transition probabilities are quite well predicted by this theory [4].

In the Pt^{194} nucleus, which has been extensively investigated by the present author, evidence has been found for 29 excited states, with energies extending up to 2.3 MeV. Since collective effects are strongly suggested through the $E2$ multipolarity of some transitions, we find some interest in trying to classify the states according to their intrinsic excitation. Thus, it was originally thought that each state of particle excitation would be associated with a band of collective vibration. It was thought profitable to illuminate this question by investigating whether such a situation exists in simpler cases. It was natural, therefore, to look for collective excitation of the ground states, or of low lying states of odd nuclei.

Experimental data

It is known that the energy of the first excited state of an even nucleus varies in a reasonably smooth way as neutron pairs are added to it. Adopting the vibrational picture, a similarly smooth change might occur as an odd neutron or proton is added, since the pairing process itself not necessarily helps to maintain a spherical equilibrium and, therefore, rather the number of nucleons in access of a closed shell may be expected to be the deciding factor. In a weak coupling picture, on the other hand, the core is not much influenced by the extra nucleon, and the influence is expected to be less the lower the orbital angular momentum of the odd particle.

For the identification of possible vibrational states or asymmetric rotor states in odd nuclei, it is useful to summarize the observable properties expected for such states. An $E2$ transition probability which is high in comparison to the single proton estimate, is sufficient proof of the existence of a cooperative motion of the particles. However, in order to identify states in an even and an odd nucleus as actually being produced by the same mode of collective motion, additional requirements have to be fullfilled:

(*a*) It will be assumed that the collective excitation energy of the odd nucleus should equal the average energy of the first excited state in the two neighbouring isotopes, whithin limits of approximately ten percent.

(*b*) In a weak coupling approximation, the odd particle retains a constant angular momentum, and this angular momentum adds to that of the collective motion in different manners. Consequently, on this assumption already the lowest collective state will split into several components of somewhat different energy. If the coupling is assumed stronger the situation becomes more complicated and in the asymmetric rotor model no constant of the motion exists for the odd particle. It seems probable that an observable difference between the two proposed modes of motion, the quadrupole vibration of a spherical system and the rotation of an asymmetric top, lies exactly in the number of components of this collective state. In searching for experimental evidence it will be necessary to accept any angular momentum that can be formed by combination of the spin (2) of the collective motion with that of the odd particle.

(*c*) The composite level must be required to have the same parity as the fundamental particle state. It follows that the spin of the excited state sometimes allows decay by a mixed $E2-M1$ transition, and in such cases the $E2$ character must be dominating, if the level is to be considered as a result of collective motion.

(*d*) Transitions between states of different particle excitation is expected to take place according to the selection rule $\Delta n = 0$, where n is the oscillator quantum number. This means that transitions from a vibrational state to lower particle states are forbidden, since they would involve a change of vibration as well as intrinsic motion.

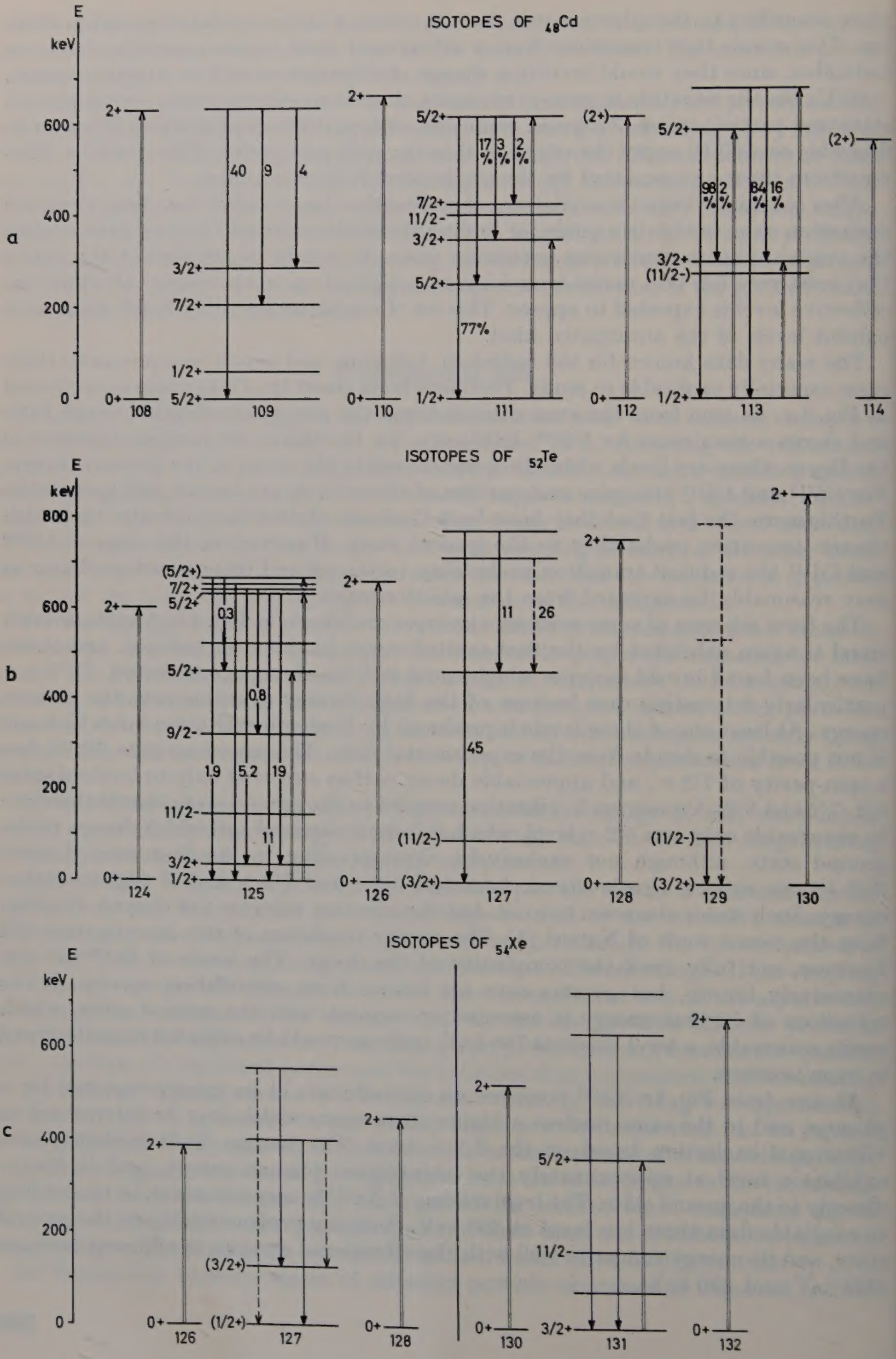
(*e*) Unlike the situation in even-even nuclei, there is no wide gap between the ground state and particle states. To avoid confusion with particle-excited states it would be desirable as well to apply the criterion that the spin and parity of the level be different from those accomodated by the single particle level schemes.

After scanning various compilations of radioactive decay and of data from Coulomb excitation so as to obtain a guide for finding the evidence looked for, we have studied the original papers concerning promising cases. It should be stressed at the outset that relatively few odd nuclei have been investigated up to the energy at which the collective level is expected to appear. This set of nuclei, on the other hand, frequently exhibit levels of the anticipated kind.

The many data known for the cadmium, tellurium and xenon isotopes make these cases especially profitable to study. Pertinent facts about the Cd isotopes are collected in Fig. 1*a*. As seen from the even mass isotopes the energy of vibration varies little and shows a maximum for Cd^{110}. Evidently, for the three odd isotopes included in the figure, there are levels which fit quite smoothly the trend of the phonon energy. For Cd^{111} and Cd^{113} the spins and parities of these levels are known and acceptable. Furthermore, the fact that they have been Coulomb-excited demonstrates their high electric transition probability to the ground state. However, in the cases of Cd^{109} and Cd^{111} the reduced transition probability to the ground state is not as strong as may reasonably be expected from the selection rules.

The level schemes of some tellurium isotopes are shown in Fig. 1*b*. A quite smooth trend is again exhibited by the first excited states in the even isotopes, and states have been found in odd isotopes which could well be of analogous nature. Te^{125} is a particularly interesting case because of the high density of states near the phonon energy. At least one of these levels is produced by Coulomb excitation but which one is not possible to decide from the experimental data. The parent nucleus (Sb^{125}) has a spin-parity of $7/2+$, and appreciable decay is thus expected only to levels of spins 5/2, 7/2 and 9/2. A quadrupole vibration coupled to the ground state should therefore be observable only as a $5/2+$ level, which is indeed observed and which decays to the ground state, although not exclusively. Corresponding to the first excited state ($3/2+$) one expects two levels of characters $5/2+$ and $7/2+$ and of slightly higher energy. Such states also seem to exist, but the selection rules are not obeyed, to judge from the recent work of Narcisi [5]. The energy resolution of this investigation did however, not fully meet the complexity of the decay. The levels of Te^{129} are not extensively known, but gamma rays are known from scintillation spectra. If the transition of highest energy is assumed to connect with the ground state, which seems reasonable, a level exists at 788 keV, quite as would be expected from the trend in even isotopes.

As seen from Fig. 1*c* Xe^{127} possesses an excited state at an energy expected for a phonon, and in the same nucleus a higher state exists which may be interpreted as vibrational excitation based on the $3/2+$ level. The isotope Xe^{131} evidently also exhibits a level at approximately the interpolated phonon energy, and it decays directly to the ground state. The level scheme of Xe^{127} is very uncertain, but according to available data there is a level at 406 keV, decaying predominantly to the ground state, and its energy compares well with the vibrational energies in adjacent isotopes (386 keV and 450 keV).


ISOTOPES OF $_{48}$Cd
E
keV
0
200
400
600
a
2+
0+
108
3/2+
7/2+
1/2+
5/2+
40
9
4
109
2+
0+
110
5/2+
7/2+
11/2-
3/2+
5/2+
1/2+
17 %
3 %
2 %
77%
111
(2+)
0+
112
5/2+
3/2+
(11/2-)
1/2+
98 %
2 %
84 %
16 %
113
(2+)
114
ISOTOPES OF $_{52}$Te
E
keV
0
200
400
600
800
b
2+
0+
124
(5/2+)
7/2+
5/2+
5/2+
9/2-
11/2-
3/2+
1/2+
0.3
0.8
1.9
5.2
19
11
125
2+
0+
126
(11/2-)
(3/2+)
11
26
45
127
2+
0+
128
(11/2-)
(3/2+)
129
2+
130
ISOTOPES OF $_{54}$Xe
E
keV
0
200
400
600
c
2+
0+
126
(3/2+)
(1/2+)
127
2+
0+
128
2+
0+
130
5/2+
11/2-
3/2+
131
2+
0+
132

There are a few additional cases, in the region of medium mass nuclei, where levels in odd nuclei conform with the trend of the first excited states in neighbouring even isotopes. These cases are: Fe^{55}, Ni^{61}, Ge^{73}, Se^{77}, Sr^{89}, Zr^{91}, Zr^{93}, Mo^{95}, Mo^{97}, Ru^{101}, and Ba^{137}.

Among the platinum isotopes there may be a similar smoth trend of excited states. In fact, Pt^{191} is reported to have a state at 300 keV, to be compared to 317 keV for Pt^{192}. The first excited state in Pt^{194} lies at 328 keV, and in the decay of Au^{193} to Pt^{193} there is an $E2$ transition of energy 318 keV which could not be located on coincidence basis.

It is noticed that the variation of the energies of the levels is more abrupt as a function of proton number than of neutron number. No support has been found for a vibrational level in nuclei of odd atomic number. Especially the levels of the odd-odd nuclei are only slightly known at energies of a few hundred keV and higher.

Coulomb excitation would be generally effective in producing vibrational or rotational levels of the kind discussed, but the detection, which is generally made by scintillation methods, involves too poor resolving power to yield more than a few strong transitions. Furthermore, odd nuclei usually have low abundancies or are unstable.

A recently published paper by Davydov considers the coupling of an odd nucleon (in the state $j = \frac{1}{2}$) to an axially unsymmetric core [6]. The result for the deformation region $\gamma \simeq 30^\circ$, which is of interest here, is a set of low lying levels of spins 3/2, 5/2, 7/2. Selection rules for these levels are, however, not yet available. As this approach has proved successful in explaining the features of even-even nuclei, it may be hoped that it will make the collective effects in odd nuclei more understandable. So, for instance, it may give an explanation of the puzzling, low lying states that are produced in Coulomb excitation in nuclei such as Cd^{111}, Cd^{113}, and Xe^{131}.

Discussion

It is realized that the experimental evidence for vibrational or rotational levels in odd nuclei, as presented here, is far from convincing. The author would emphasize the difficulty of distinguishing a collective type of state in the manifold of particle states, especially since theories at present do not predict to what extent the odd particle or particles distort the energies of collective excitation. We are, however, led to believe that the effect has not been sought to any great extent by experimentalists in the past, and, unless it is intentionally studied it is likely to be overlooked. As a consequence of the pairing energy, the energy available in a decay leading to an odd nucleus is on the average less than in a decay to an even-even nucleus, which of course reduces the population of the vibrational state relative to that of the ground state. Moreover, the feeding in radioactive decay is expected to be weak because of competition with the feeding to several low lying states. The conversion coefficients of transitions from the particle states are higher and therefore make the particle effects dominate even more in conversion spectra. Since there is a tendency to regard

Fig. 1. Level schemes for some cadmium, tellurium and xenon isotopes. Data that is not of interest has been excluded. For cadmium the intensities refer to the dexcitation of a certain level. The values given for the tellurium isotopes are taken from the beta decay.

weak lines as less important, the chances of detection of collective effects become even less. Studies of such effects would, however, greatly help to clarify the excitation process in nuclei.

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